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A Model for unusual pulsed X-ray emission from PSR J1119 - 6127

George I. Melikidze^{1,2}, Janusz Gil¹ and Andrzej Szary¹

¹ Institute of Astronomy, University of Zielona Góra, Lubuska 2, 65-265, Zielona Góra, Poland

² Abastumani Astrophysical Observatory, Al. Kazbegi ave. 2a, 0160, Tbilisi, Georgia

Abstract. We propose a model, which naturally explains an unusual thermal X-ray emission, observed from PSR J1119-6127. The model is based on the assumption that the pulsar magnetic field near the stellar surface differs significantly from the pure dipole field. We show that the structure and curvature of the field lines can be of the kind that allows the pair creation in the closed field line region. The created pairs propagate along the closed field lines and heat the stellar surface beyond the local poles. It is demonstrated that such a configuration can be easily realized.

Thermal X-ray emission seems to be a quite common feature of the radio pulsars. On the other hand characteristics of such radiation allows us to get a lot of information about the polar cap region of the pulsars. Standard model of the radio pulsars assumes that there exists the Inner Acceleration Region (IAR) above the polar cap where the electric field has a component along the magnetic field lines. The particles (electrons and positrons) are accelerated in both directions: outward and toward the stellar surface. Consequently, outstreaming particles generate the magnetospheric (radio and high-frequency) emission while the backstreaming particles heat the surface and provide necessary energy for the thermal emission. In such a scenario X-ray diagnostics seems to be an excellent method to get insight into the most intriguing regime of the neutron star.

The black body fit allows us to obtain directly the bolometric size (A_{bol}) and temperature (T_s) of the polar cap. In most cases A_{bol} is much less than the conventional polar cap area. It can be easily explained by assuming that the surface magnetic field of pulsars differs significantly from the pure dipole one. Then, one can estimate an actual surface magnetic field by the magnetic flux conservation law as $b = A_{\text{bol}}/A_{\text{pc}} = B_d/B_s$. Here $B_d = 2 \times 10^{12} \left(P \dot{P}_{15} \right)^{1/2}$, P is the pulsar period in seconds and $\dot{P}_{15} = \dot{P}/10^{15}$ is the period derivative. In most cases $b \sim 10 - 60$, which implies $B_s \gg B_d$, while $T_s \sim (2 - 4) \times 10^6$ K. Recently Gil, Melikidze & Zhang (2005, 2006, GMZ06 henceforth) have shown that the model of the Partially Screened Gap

(PSG) can interpret the observational data not only qualitatively but also quantitatively.

The X-ray observations of PSR J1119-6127 showed quite unusual features of this pulsar. As it was demonstrated by Gonzalez et al. (2005, G05 hereafter) the *XMM-Newton* observations denote the thermal feature of the pulsed X-ray emission from this pulsar. The derived characteristics of the black body fit are as follows: $A_{\text{bol}} = 3.6^{+4.9}_{-0.6} \times 10^{13} \text{ cm}^2$ and $T_s = 2.4^{+0.3}_{-0.2} \times 10^6 \text{ K}$. The X-ray flux is estimated as $L_x = 2.0^{+2.5}_{-0.4} \times 10^{33} \text{ erg s}^{-1}$. Let us note that both A_{bol} and L_x depend on the distance estimation, which for this pulsar is estimated as $D = 8.4 \pm 0.4 \text{ kpc}$ (Caswell et al. 2004), while Cordes-Lazio NE2001 (2002) Electron Density Model suggests the distance estimate as $D = 17 \text{ kpc}$, ($10 < D < 50$). Therefore, if the distance is underestimated the flux as well as A_{bol} are even larger.

PSR J1119-6127 was discovered in the Parkes Multi-beam Pulsar Survey (Camilo et al. 2000). The observed parameters of the pulsar are as follows: $P = 0.408 \text{ s}$, $P\dot{P}_{15} = 4.0 \times 10^3$, $B_d = 8.2 \times 10^{13}$ (note a slight inaccuracy in estimation of B_d by G05) and the spin-down energy loss $L_{\text{sd}} = 2.3 \times 10^{35} \text{ erg s}^{-1}$. The conventional polar cap area is about $A_{\text{pc}} = 1.6 \times 10^9 \text{ cm}^2$. As we see the efficiency of X-ray emission defined as $\xi = L_x/L_{\text{sd}} \sim 0.009$ is of the same order of magnitude as it is for other pulsars, while the bolometric area A_{bol} exceeds $A_{\text{pc}} 2 \times 10^3$ times.

1. The model

We propose the model, which is based on the assumption that the surface magnetic field of pulsar differs greatly from the dipolar field. The curvature and strength of the surface field can be much bigger than those which follow from the simple dipolar geometry. This assumption seems to be quite natural and as it was mentioned above supported by the X-ray observations of the rotation-powered pulsars (GMZ06). Gil, Melikidze, Mitra (2002) proposed that the actual surface magnetic field can be modelled as a superposition of the global dipole field and crust-anchored small scale magnetic anomalies. They also provided corresponding numerical formalism. Such an approach allows to get some insight on the geometry, as well as to esti-

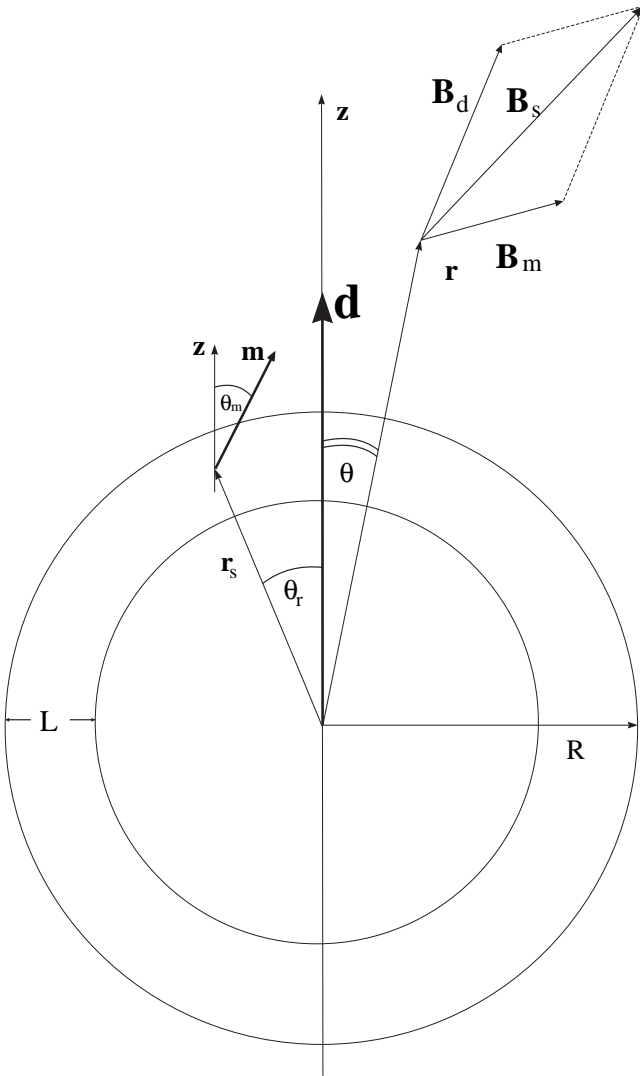


Fig. 1. Superposition of the star centered global magnetic dipole \mathbf{d} and crust anchored local dipole \mathbf{m} placed at $\mathbf{r}_s = (r_s \sim R; \theta = \theta_r)$ and inclined to the z-axis by an angle θ_m . The actual surface magnetic field at radius vector $\mathbf{r} = (r; \theta)$ is $\mathbf{B}_s = \mathbf{B}_d + \mathbf{B}_m$, where $\mathbf{B}_d = 2\mathbf{d}/r^3$, $\mathbf{B}_m = 2\mathbf{m}/|\mathbf{r} - \mathbf{r}_s|$, r is the radius (altitude) and θ is the polar angle (magnetic colatitude). R is the radius of the neutron star and L is the crust thickness.

mate the curvature of the field lines. Fig. 1 represents the general picture of the model.

Fig. 3 is a cartoon of the magnetic field lines for any general symmetric case (see figure caption for details). The corresponding magnetic field strength is shown in Fig. 2, while Fig. 4 shows the curvature of the open magnetic field lines as a function of the altitude. As it is clear from Fig. 4 the crust-anchored magnetic anomalies can alter not only a value of the curvature but also its sign. In the pure dipole configuration photos radiated almost tangent to the magnetic field lines always propagate inward, i.e. in the

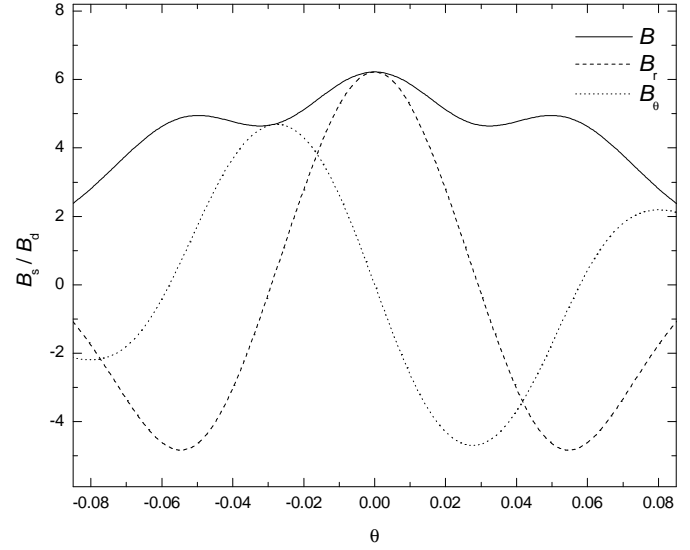


Fig. 2. The magnetic field and its components near the stellar surface at the polar cap region.

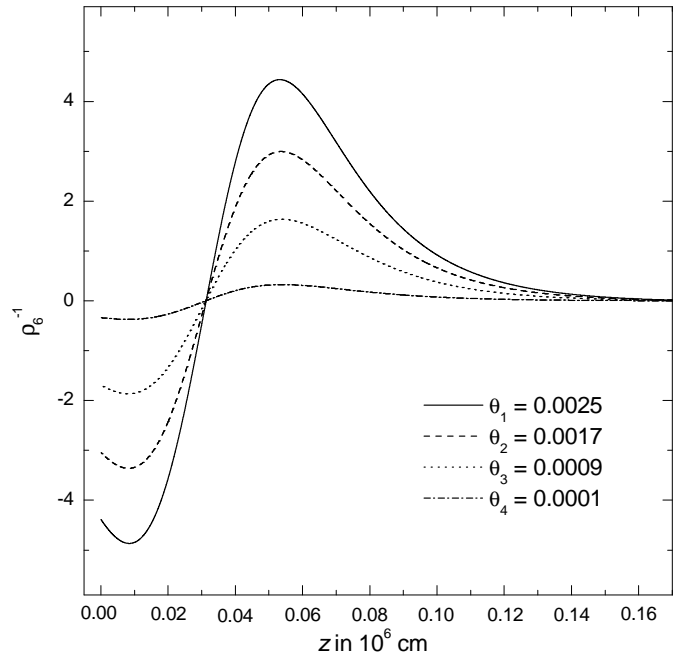


Fig. 4. Curvature ($1/\rho_6$) of the field lines vs of the altitude. Various θ -s define the footpoints of the corresponding field lines at the stellar surface.

direction of the global dipole axes. Therefore, pair creation can occur only in the open field line region. However, in the presence of the local anomalies the field configuration changes drastically. Despite the fact that Fig. 1 represents some particular case, the change of the curvature sign is quite general.

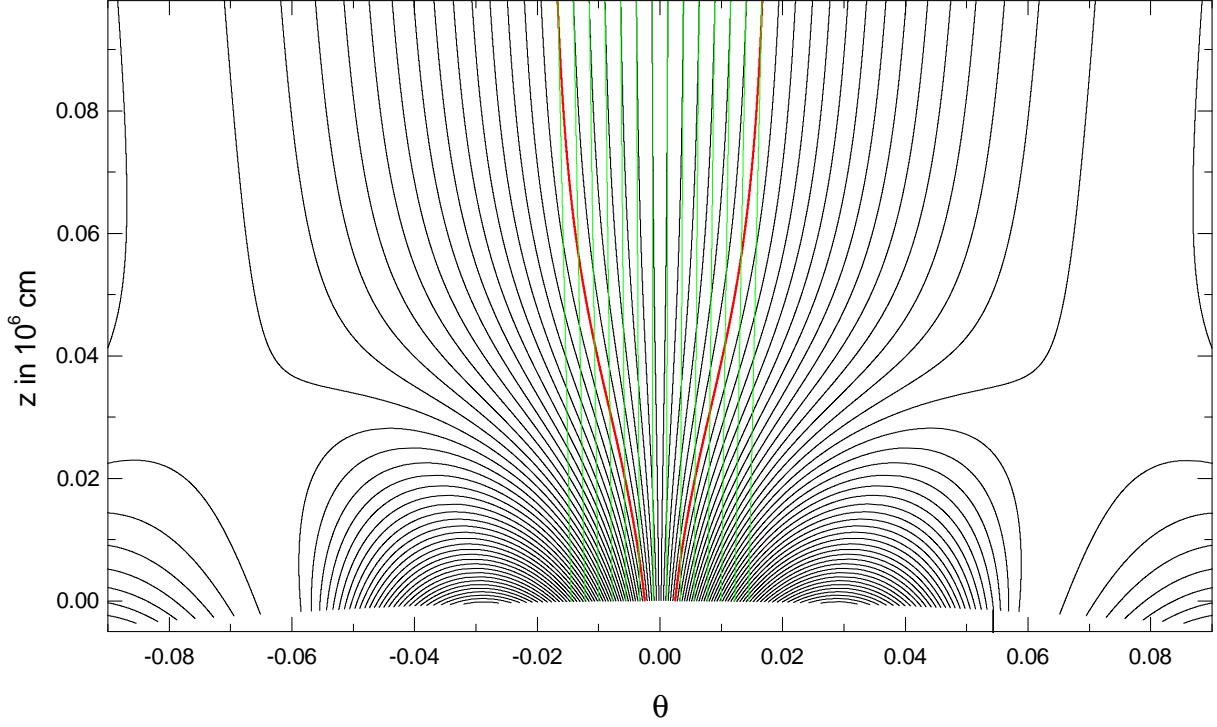


Fig. 3. Cartoon of the magnetic field lines in the polar cap region. There are three crust anchored magnetic anomalies in this case: the central one is aligned with the global dipole, while two others are directed to the opposite direction. Distance between the local dipoles is 500 meters. The green lines represent the pure dipole field. The red lines correspond to the last open field lines, which at high altitudes coincide with the dipole field lines. θ is the magnetic colatitude in radians.

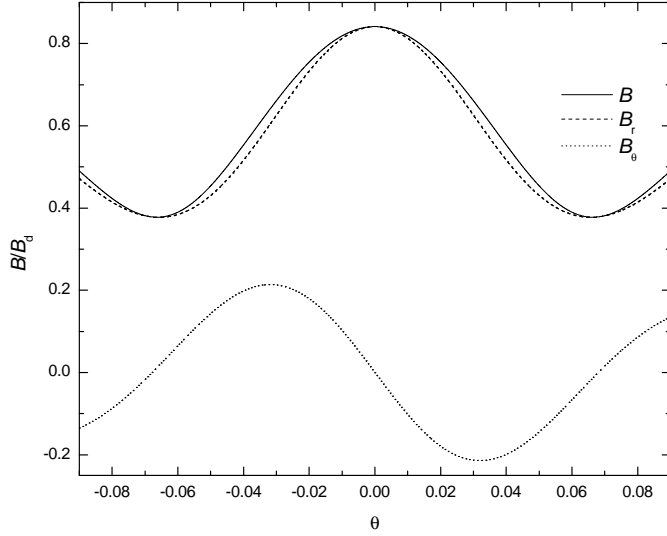


Fig. 5. The magnetic field and its components at the altitude that corresponds to the strongest curvature of the field lines.

2. Estimation of the particles Lorentz factor

Let us estimate the characteristic Lorentz factors of the particles accelerated in IAR. Following GMZ06 we use PSG model for IAR. The efficiency of the thermal X-ray

emission from the drifting pulsars is quite well explained by this model (GMZ06). In addition GMZ06 gives a proper estimate for the surface temperature if the bolometric surface coincides with the actual polar cap surface. In the case under consideration the latter condition is not satisfied. Therefore, we should estimate the screening factor (see GMZ06 for details) using only efficiency of the X-ray emission, while the temperature and A_{bol} should be defined by the heating-cooling balance.

The mean Lorentz factor of the accelerated particles is the main parameter that defines the energy outflow from the polar cap. The Near Threshold (NT) condition (Gil & Melikidze 2002) implies that the energy of the pair-creating photon should be

$$\hbar\omega = 2m_e c^2 / \sin\vartheta \sim 1.6 \times 10^{-3} \rho_6 / h_3. \quad (1)$$

Here $h_3 \equiv h/(10^3 \text{cm})$, h is the gap height and $\rho_6 \equiv \rho/(10^6 \text{cm})$ ρ is the curvature radius of the local magnetic field lines. In the gap two kinds of photons can generally exist: the photons (with energy $\hbar\omega_{\text{cr}} \sim 1.4 \times \gamma^3 / \rho_6$) emitted by the curvature radiation and/or the photons (with energy $\hbar\omega_{\text{ics}} \sim \gamma b$) generated by the inverse Compton scattering process. For the simplicity we only consider the curvature radiation dominated PSG. The energy of the curvature photons writes:

$$\hbar\omega_{\text{cr}} \sim 1.4 \times 10^{-5} \gamma_6^3 \rho_6^{-1}. \quad (2)$$

Combining eqs.(1) and (2) we can estimate the NT gap height as $h_3 \sim 1.2 \times 10^2 \rho_6^2 / \gamma_6^3$. On the other hand, using the expression for the accelerating potential drop and taking into account the screening factor we can express γ_6 as (GMZ06): $\gamma_6 \sim 4.6 \times b P^{-1} h_3^2 \eta$. Then, using the NT condition we finally get the following expression for the characteristic Lorentz factors of particles accelerated in PSG

$$\gamma_6 \sim 5 \left(P^{-1} b \eta \rho_6^4 \right)^{\frac{1}{7}}. \quad (3)$$

3. Emission and absorbtion of the curvature photos

The power of the curvature radiation writes:

$$L_{\text{cr}} = 4.6 \times 10^{-9} \frac{\gamma_6^4}{\rho_6^2} = 4.6 \times 10^3 \frac{\gamma_6^4}{\rho_6^2} \text{ ergs}^{-1}. \quad (4)$$

Let us define \bar{L}_{cr} as:

$$\bar{L}_{\text{cr}} \equiv \frac{L_{\text{cr}}}{\gamma m_e c^2} = 5.6 \times 10^3 \frac{\gamma_6^3}{\rho_6^2}. \quad (5)$$

Now we can claim that the particle can emit (by means of the curvature radiation) the energy, which is comparable with its energy while passing the distance of the order of ρ (i.e. during time ρ/c) if the condition

$$\frac{\gamma_6^3}{\rho_6} \gtrsim 5.4 \quad (6)$$

holds. It is clear from Fig. 4 and eq. (3) that the filed lines have enough curvature to satisfy condition (6). Fig. 4 shows that the particles accelerated in the outer ring of the open field lines should pass the region where the curvature is high. The surface of this ring constitutes the major part of the polar cap, therefore the particles created in the closed field line region carry energy comparable with the energy of the outstreaming particles, i.e. comparable with the total energy available in IAR. At the same time the energy of the curvature photons is about

$$\hbar \omega_{\text{cr}} \sim 17 \frac{\gamma_6^3}{\rho_6} m_e c^2, \quad (7)$$

thus it is high enough for the pair creation.

Let us now estimate a free path of the curvature photons emitted at altitudes about few hundred meters from the stellar surface. Using Erber's (1966) approximation and eqs. (6) and (7) we can express the photon free path as:

$$l_{\text{ph}} \sim 4 \times 10^{-5} \left(\frac{B_q}{B_{\perp}} \right) \exp \left(0.9 \frac{B_q}{B_{\perp}} \right) \quad (8)$$

Here $B_q = 4.414 \times 10^{13}$ G is so called quantum magnetic field and B_{\perp} is a component of the magnetic field which is perpendicular in respect to the photon propagation direction. The components of the magnetic filed at the altitude where the curvature reaches its maximum are plotted in

Fig. 5. One can see that the photons should be emitted almost along the radial component B_r of the magnetic filed as B_{θ} is much smaller. Therefore, the photon free path depends on $B_{\theta} \sim B_{\perp}$. Estimations show that l_{ph} varies from few hundred meters ($B_{\perp}/B_q = 0.05$) up to a few tens of kilometers.

4. Discussion and Conclusion

We have demonstrated that if the crust anchored magnetic anomalies at the surface of the neutron star are strong enough to alter the curvature of the magnetic field lines, there exist favorable conditions for pair production in the closed field line region. All those pairs move along the field lines, reach the stellar surface in the region of close field lines and heat it. The hot surface emits the thermal radiation with the characteristic temperature that is defined by the energy balance between the particle flux and the bolometric power. Therefore, the observed thermal radiation comes not only from the polar cap region but also from the nearby area. For the parameters of PSR J1119 - 6127, the particle flux can have enough power to support the observed thermal emission if eq. (6) is satisfied, which seems quite reasonable.

The efficiency of the thermal X-ray emission is defined in the same way as it is presented by GMZ06, i.e. the efficiency depends on the potential drop of the inner acceleration region. If the bolometric surface is smaller than conventional polar cap area, then the characteristic temperature of the blackbody fit is also defined by the parameters of the partially screened gap, i.e. by the thermostatic regulation of the screening parameter (Gil et al. 2003). In the case of PSR J1119 - 6127 the blackbody temperature of the X-ray emission is simply defined from the heating-cooling balance of the hot surface. The radiation comes from the closed field line region, where the electric field is always perpendicular to the magnetic field, consequently there no partial screening is possible. We believe that it is another argument in favour of the partially screened gap model for the inner acceleration region of pulsars.

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References

- Camilo, F., Kaspi, V. M., Lyne, A. G., et al. 2000, ApJ, 541, 367
- Camilo, F., Kaspi, V. M., Lyne, A. G., et al. 2005, ApJ, 630, 486
- Cordes, G.M. & Lazio, T.J.W. 2002, astro-ph/0207156
- Gonzalez, M.E., Kaspi, V.M., et al. 2005, ApJ, 630, 489
- Erber, T. 1966, Rev. Mod. Phys., 38, 626
- Gil J. & Melikidze G.I., 2002, ApJ, 577,909
- Gil, J., Melikidze G.I., & Geppert, U. 2003, A&A, 407, 315
- Gil, J., Melikidze, G.I. & Mitra D. 2002, A&A, 388, 235

- Gil, J., Melikidze, G. I. & Zhang, B. 2005, arXiv:astro-ph/0512653
- Gil, J., Melikidze, G. I. & Zhang, B. 2006, arXiv:astro-ph/0601613 (GMZ06)